MECHANICAL JOINING OF THERMOPLASTIC CARBON-FIBER REINFORCED POLYMER TO DIE-CAST MAGNESIUM

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Presenter: Keerti Kappagantula (PNNL)

Pacific Northwest National Laboratory, Oak Ridge National Laboratory

DOE-VTO AMR

Project ID # MAT-139

OVERVIEW

Timeline

- Start: FY18
- Finish: FY20
- Percent complete: 80%

Budget

- Total project funding
  - DOE share – $550,000
  - PNNL – $250,000
  - ORNL – $300,000
  - Contractor share - None

Barriers

- Magnesium (Mg) to carbon fiber reinforced polymer (CFRP) joints are limited by:
  - Lack of high-volume joining processes[1]
  - Galvanic corrosion[2]
  - Lack of design knowledge

[1]Pg. 3, U.S. DRIVE Materials Technical Team Roadmap, October 2017
[2]Pg. 8, U.S. DRIVE Materials Technical Team Roadmap, October 2017

Partners

- Pacific Northwest National Laboratory
- Oak Ridge National Laboratory
- BASF

RELEVANCE

Objectives

- Develop new techniques for joining Mg plates to thermoplastic (TP) or thermoset (TS) CFRP.
- Improve joint performance compared to existing dissimilar joining techniques.
- Minimize Mg corrosion using different mitigation strategies.

Impact

- First-ever comprehensive study of joining Mg and CFRP using mechanical interlocking approaches
- Novel methods for using Mg interlocks for joining Mg plates to CFRP
- Quantitative measurement of Mg galvanic corrosion in the Mg/CFRP joint
- Evaluation of polymer coating performance as corrosion mitigators

Relevance to VTO

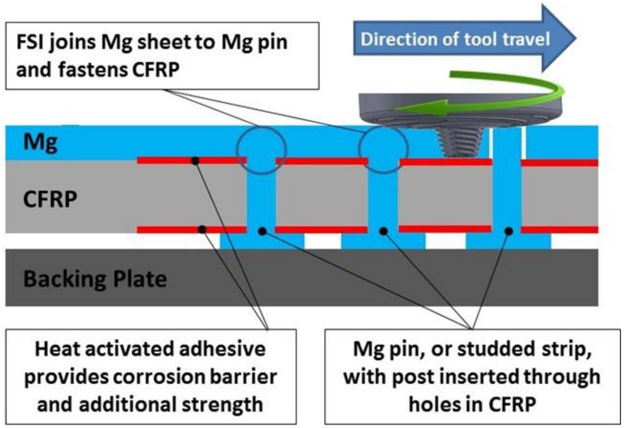
- Enable widespread use of Mg-CFRP joining technologies for automotive light-weighting.

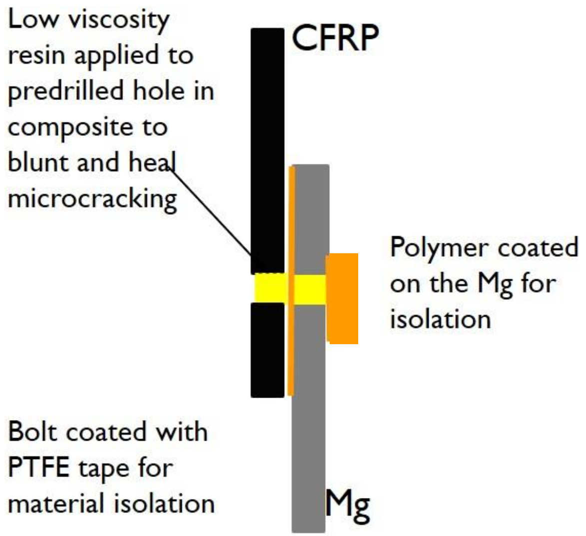
APPROACH AND MILESTONES

Mg/CFRP joining using mechanical interlocking with minimal corrosion between Mg and interlock material

- Eliminate third material (rivet) and join Mg/CFRP using Mg interlocks (pins, rivets)
  - Task 1: Friction stir interlocking of Mg and CFRP with Mg interlocks
- Isolate dissimilar materials using coating of rivet & Mg, alternative rivet materials
  - Task 2a: Bolting Mg and CFRP using 3-step polymer isolation
  - Task 2b: Friction self piercing riveting of Mg/CFRP with different coated steel rivets and/or alternative rivet materials

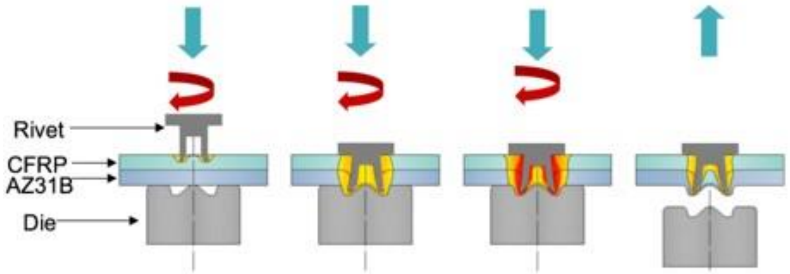
Task 1: FSI





Task 2a: Bolting

Task 2b: F-SPR



APPROACH AND MILESTONES

APPROACH

- **Investigate Mg/CFRP joining technologies with mechanical interlocking**
  - Task 1: Friction Stir Interlocking (FSI)
  - Task 2: Bolting and Friction Self-Piercing Rivet (F-SPR)
- **Develop process and tooling**
- **Characterize mechanical performance and corrosion behavior**
- **Identify corrosion mitigation strategies**

MILESTONES AND STATUS

Milestone	Due date	Status
Demonstrate void-free FSI – Spot weld with joint strength equivalent to that of FSI – Linear	December 31st 2019	Completed
Complete tensile and fatigue testing of F-SPR joints	March 20th 2020	Completed

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

APRIL 2019 – MARCH 2020

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ACCOMPLISHMENTS: TASK 1. FSI – LINEAR JOINING

DEFECT-FREE NOVEL PROCESS FOR JOINING MG & CFRP WITH MG INTERLOCKS TO MINIMIZE JOINT CORROSION

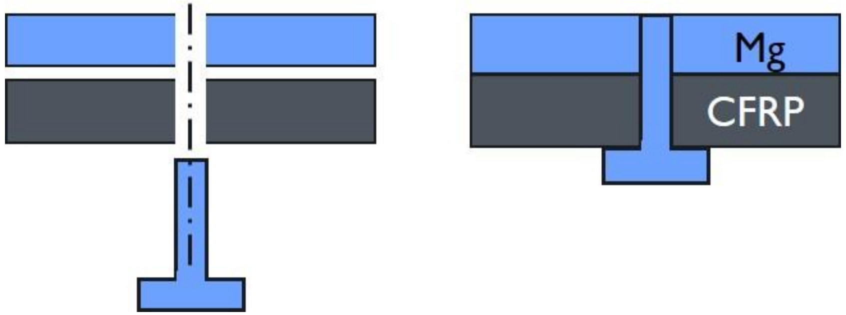

Fig. 7.1. Configuration A: Machined Mg interlocks inserted through holes drilled in Mg and CFRP plates.

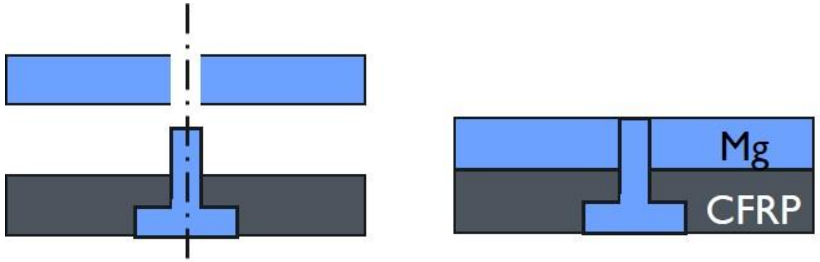

Fig. 7.2. Configuration B: Embedded Mg inserts in CFRP plate, inserted through holes drilled in Mg plate.

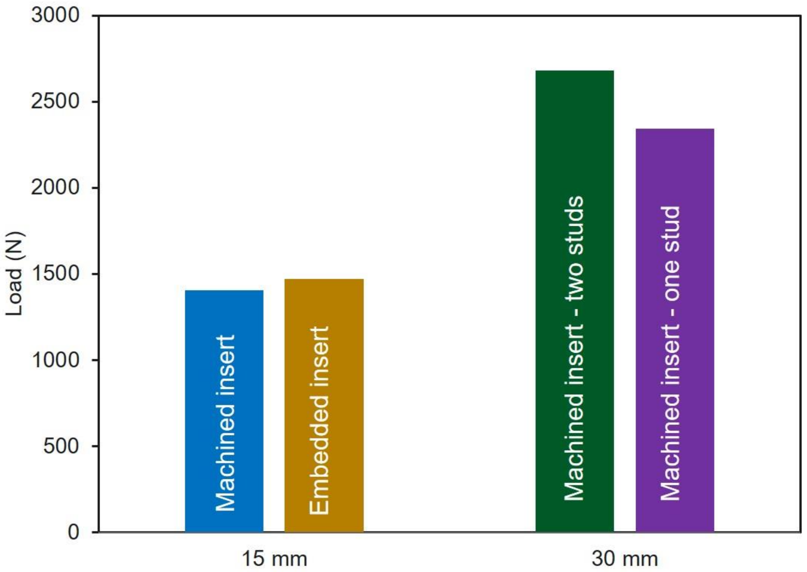

Fig. 7.3. Failure load of Mg/CFRP FSI – Linear joints with varying thickness and number of inserts.

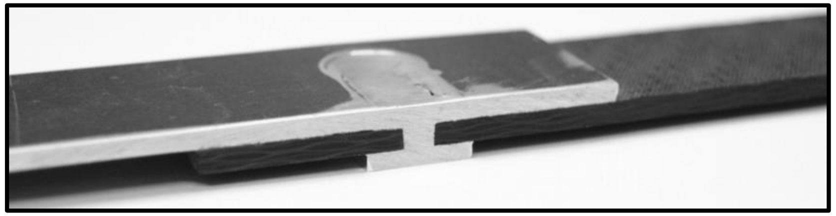

Fig. 7.4. Cross-section of FSI – Linear joint.

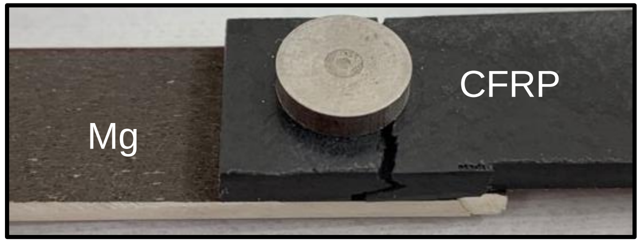

Fig. 7.5. FSI – Linear joint showing fracture in CFRP after lap-shear testing.

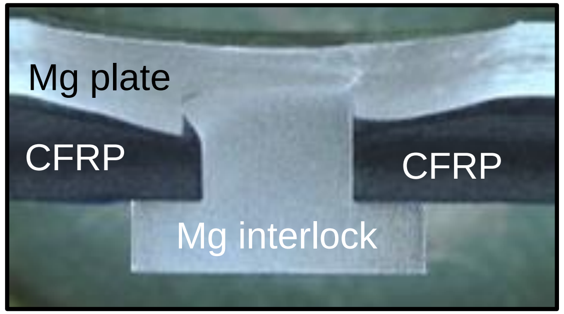

Fig. 7.6. Optical micrograph of Mg/CFRP FSI – Linear joint.

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ACCOMPLISHMENTS: TASK 1. FSI – SPOT JOINING

NEW JOINING METHOD USING LIGHTWEIGHT MG INTERLOCKS (RIVETS)

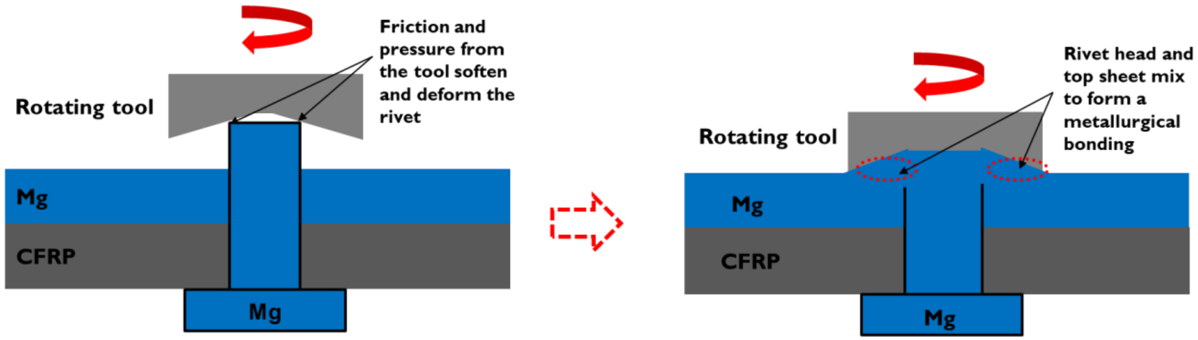

Fig. 8.1. Schematic of FSI – Spot process.

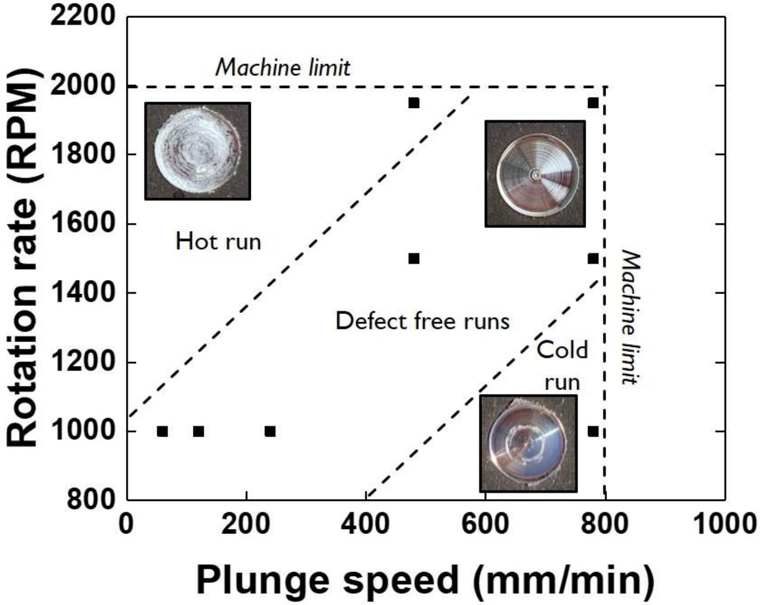

Fig. 8.2. Process parameter exploration.

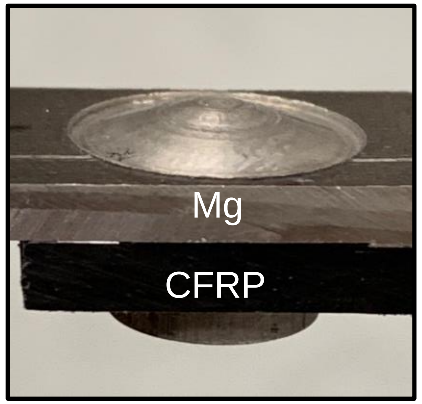

Fig. 8.3. Side-view of a Mg/CFRP FSI – Spot joint.

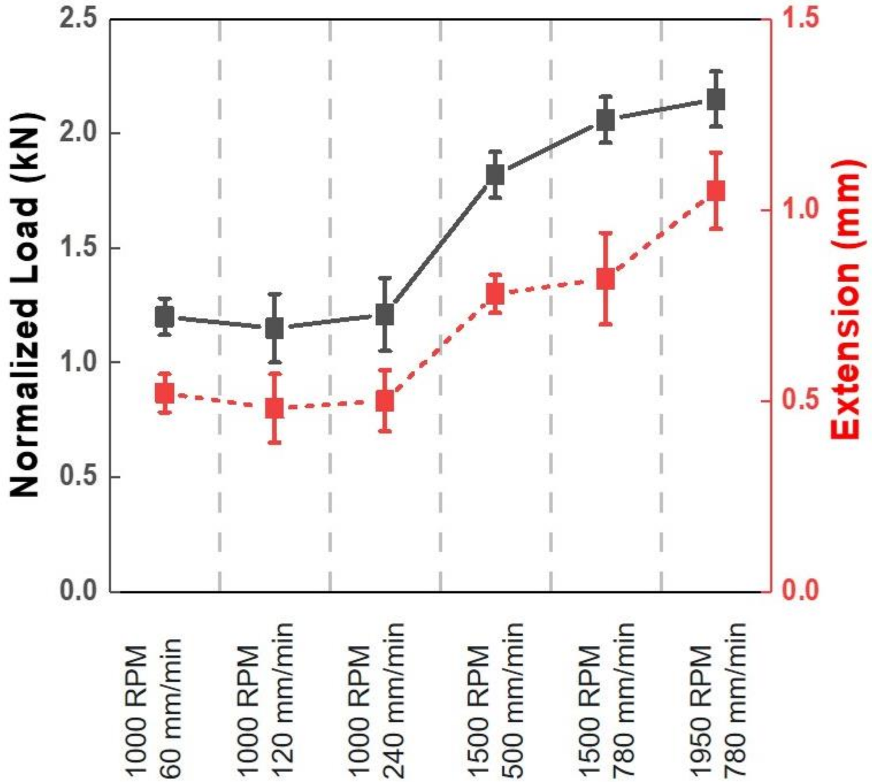

Fig. 8.4. Failure load and extension of Mg/CFRP FSI – Spot joints as a function of process parameters.

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ACCOMPLISHMENTS: TASK 1. FSI – SPOT JOINING

DEFECT-FREE ROBUST MG/CFRP JOINTS USING NOVEL MG INTERLOCKS (RIVETS)

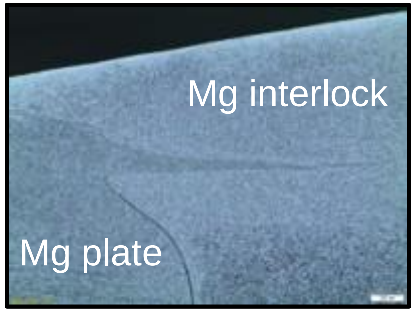

Fig. 9.1. Jagged interfaces in samples manufactured at 1000 RPM and 60 mm/min.

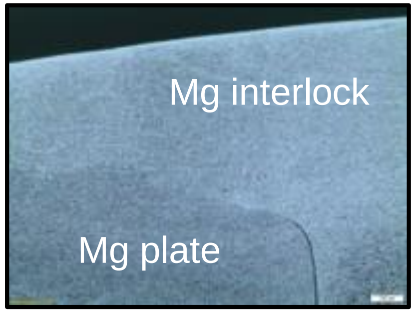

Fig. 9.2. Enhanced interfacial uniformity for samples made at 1500 rpm and 480 mm/min.

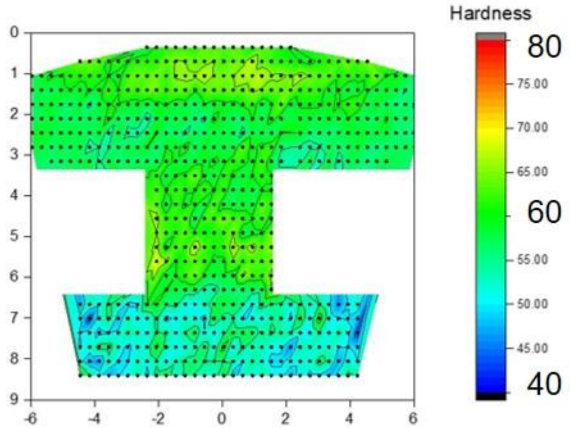

Fig. 9.3. Hardness map of Mg interlock.

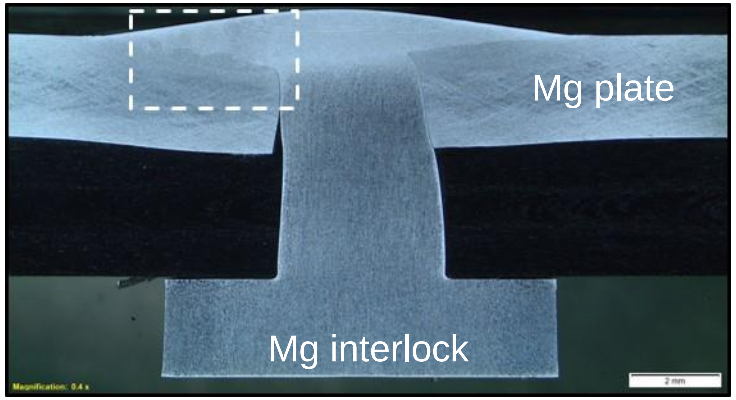

Fig. 9.4. Optical micrograph of sample made at 1500 RPM and 480 mm/min.

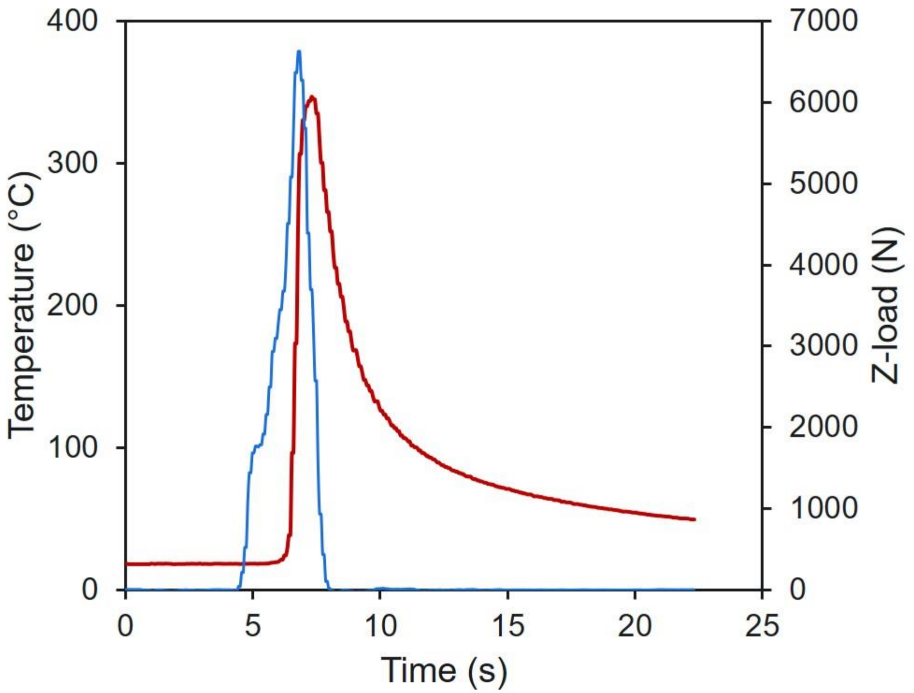

Fig. 9.5. Temperature and Z-load measured during the FSI – Spot joining process at 1500 RPM and 480 mm/min.

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ACCOMPLISHMENTS: TASK 2A. BOLTING

DECREASED CORROSION OF MG/CFRP BOLTED JOINTS WITH POLYMER COATINGS

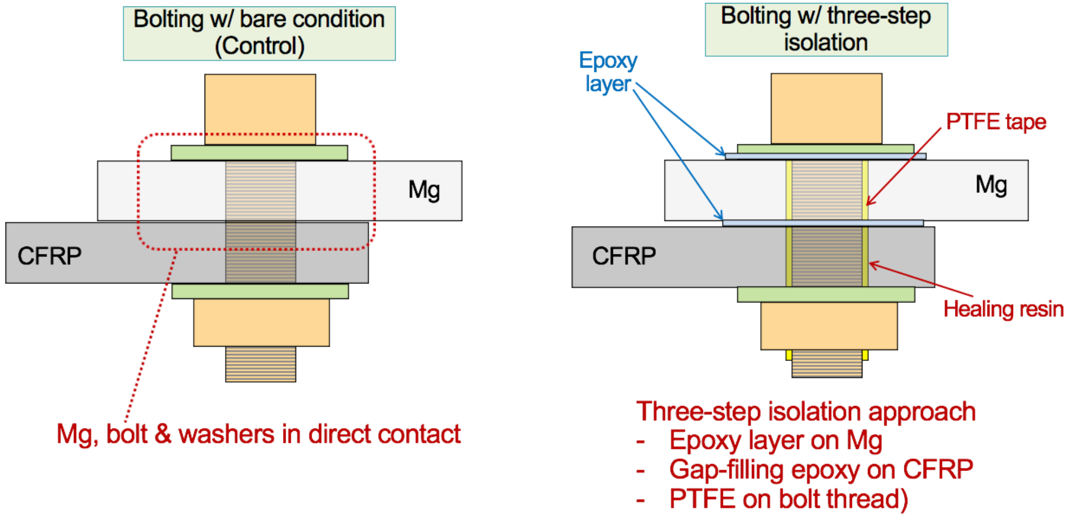


Fig. 10.1. Schematic showing the locations of polymer coatings for the bolted joints.

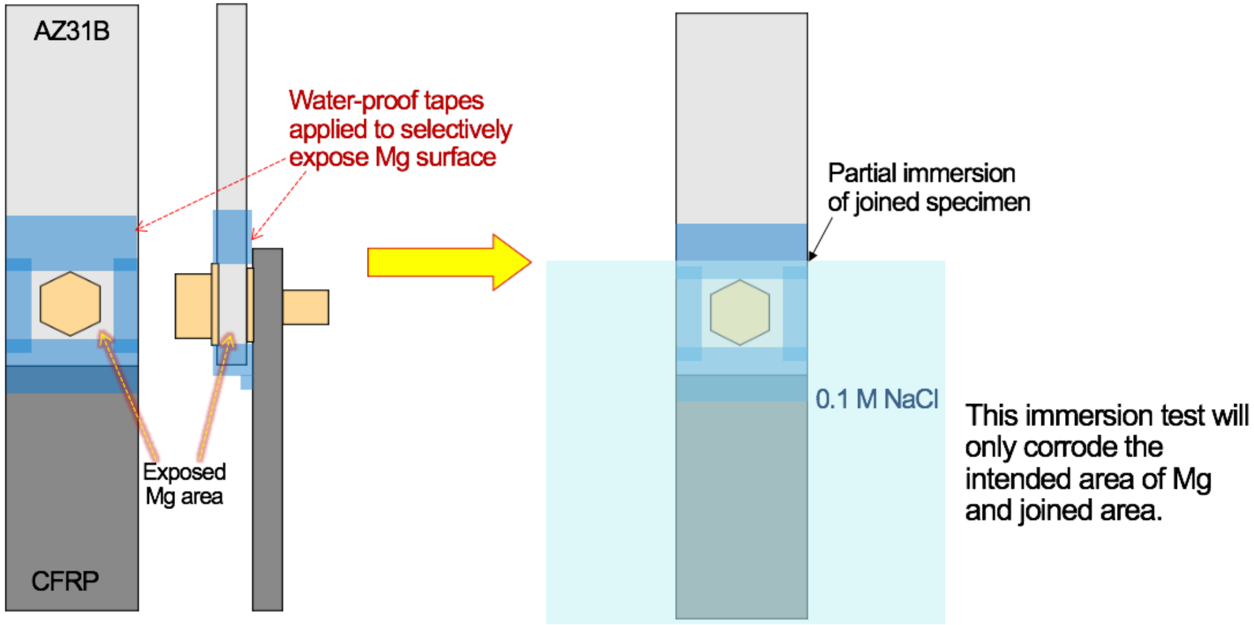
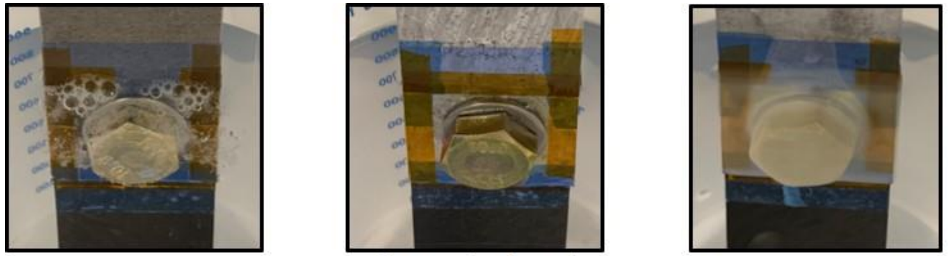


Fig. 10.2. 0.1 M NaCl immersion test

Massive evolution of hydrogen on bolt & Mg surface, without isolation, indicating Mg corrosion.



Baseline | 3-step Isolated | 3-step isolated + covered

Fig. 10.3. Bolted Mg/CFRP samples with and without isolation strategy during 0.1 M NaCl immersion.

ACCOMPLISHMENTS: TASK 2A. BOLTING

DECREASED CORROSION OF MG/CFRP JOINED WITH STEEL BOLTS USING POLYMER COATINGS

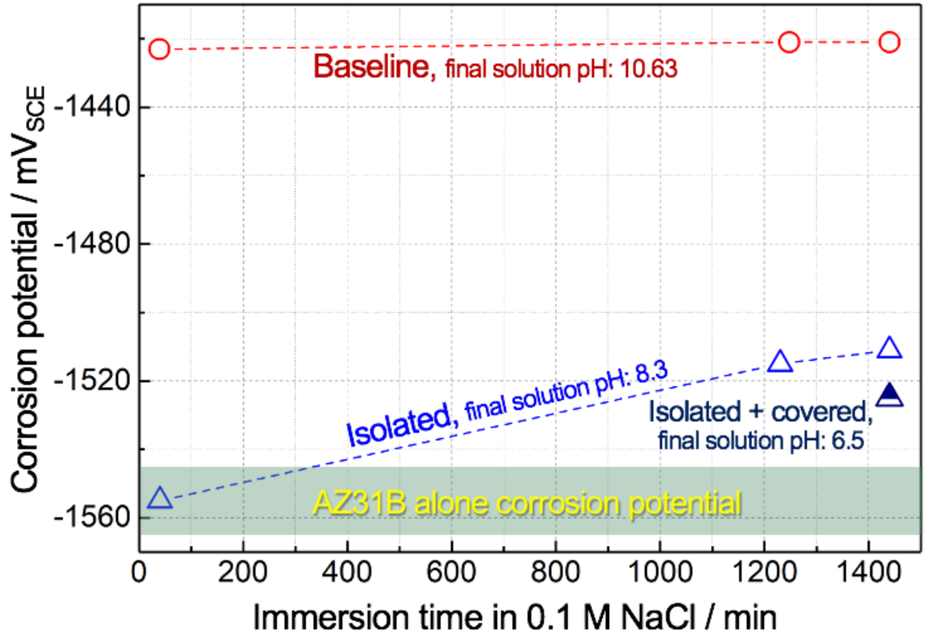
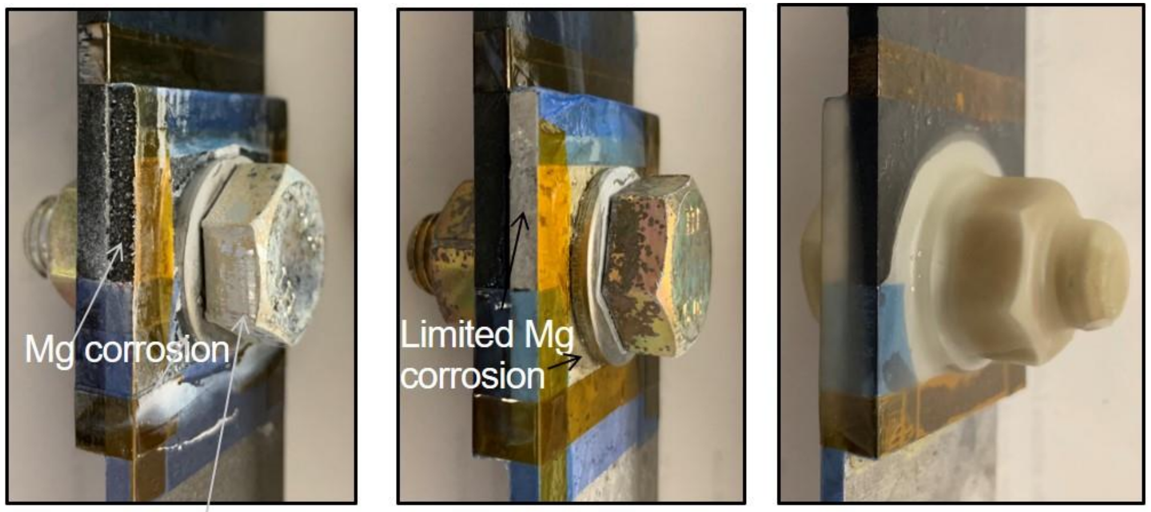


Fig. 11.1. Corrosion potential of bolted Mg/CFRP joints as a function of immersion time in 0.1M NaCl solution.



Bolt was not significantly corroded (galvanically protected) due to sacrificial anode protection

Bolt corroded as general corrosion (galvanic cell removed)

Bolt & Mg exposed area covered by beeswax did not show corrosion.

Fig. 11.2. Corrosion observed in the baseline, isolated and isolated & covered bolted Mg/CFRP samples after immersion testing.

- Higher solution pH indicates more corrosion of Mg.
- Compared to initial pH 5.8, 'Isolated + covered' had least corrosion of Mg.
- 'Isolated' also decreased Mg corrosion compared to the control.

ACCOMPLISHMENTS: TASK 2A. BOLTING

IMPROVED MECHANICAL PERFORMANCE OF BOLTED JOINTS USING 3 STEP POLYMER ISOLATION

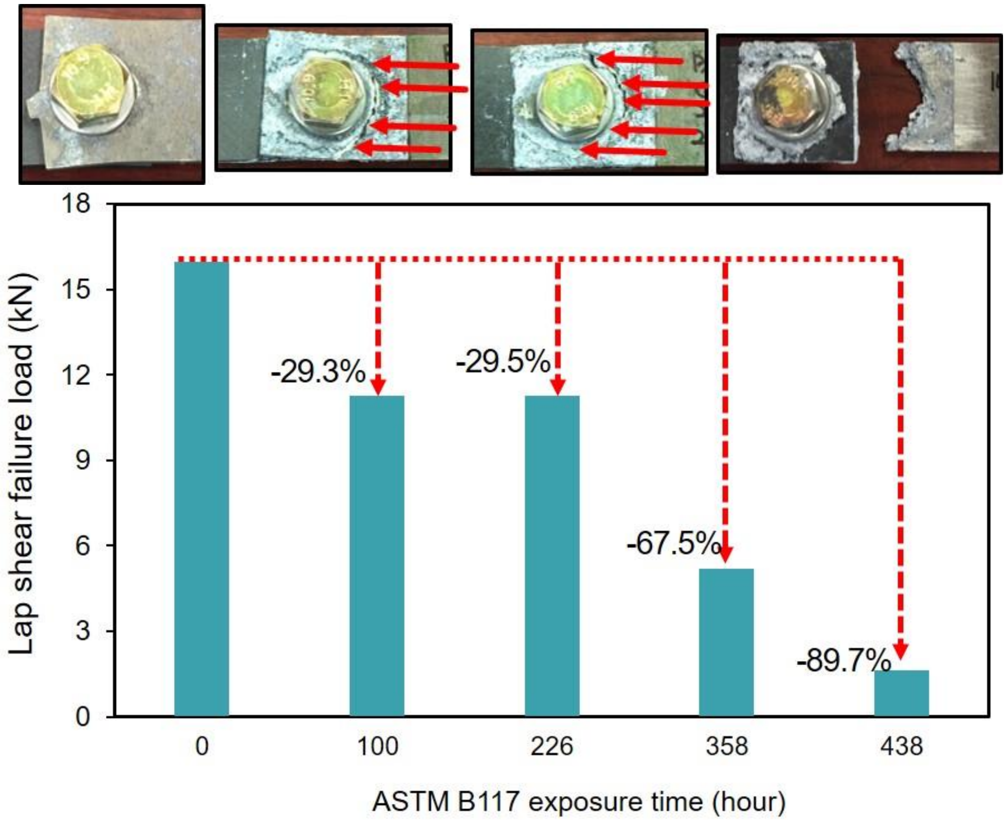


Fig. 12.1. Lap shear testing of baseline bolted Mg/CFRP joints with increasing ASTM B117 salt spray exposure time.

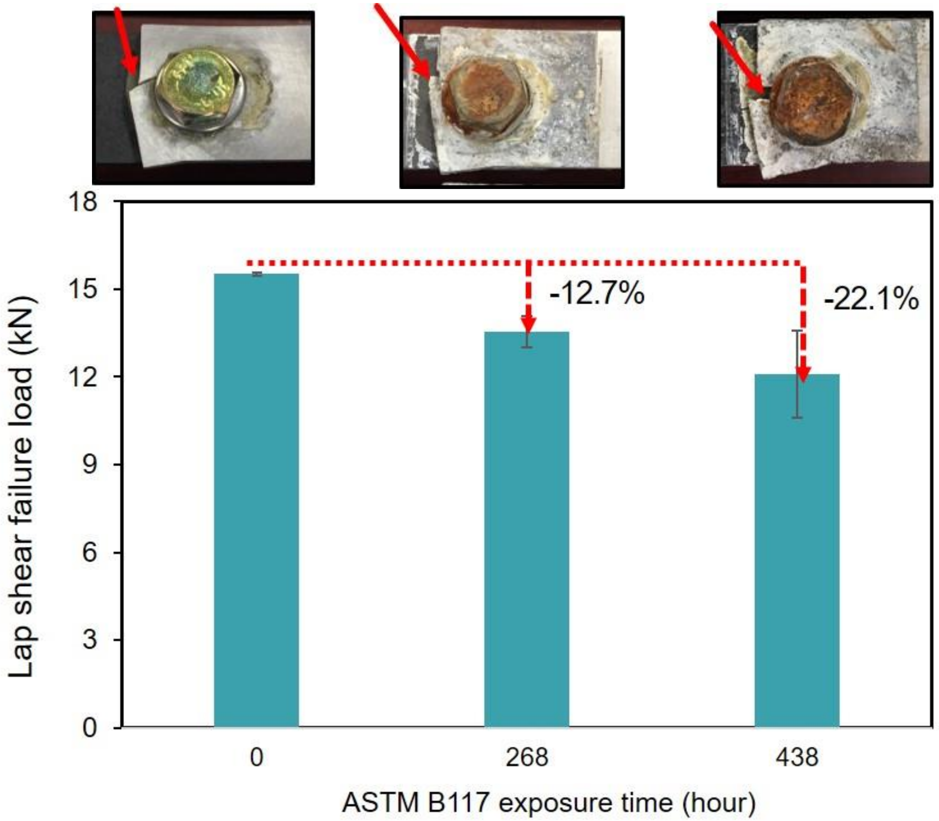


Fig. 12.2. Lap shear testing of 3-step isolated bolted Mg/CFRP joints with increasing ASTM B117 salt spray exposure time.

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ACCOMPLISHMENT: TASK 2B. F-SPR

MECHANICAL JOINT PERFORMANCE OF MG/CFRP F-SPR JOINTS

Fig. 13.1. Mechanical joint strength of F-SPR Mg/CFRP joints.

Material combination (mechanical testing)	Peak failure load (kN)	Failure location
TP CFRP-AZ31B (lap shear)	3.07 ± 0.19	Base TP CFRP
TS CFRP-AZ31B (lap shear)	5.18 ± 0.12	AZ31B pullout
Weldbonding (TS CFRP-AZ31B) (lap shear)	8.89± 0.81	Coheisve+AZ31B pullout
TS CFRP-AZ31B (cross tension)	2.81±0.11	AZ31B pullout

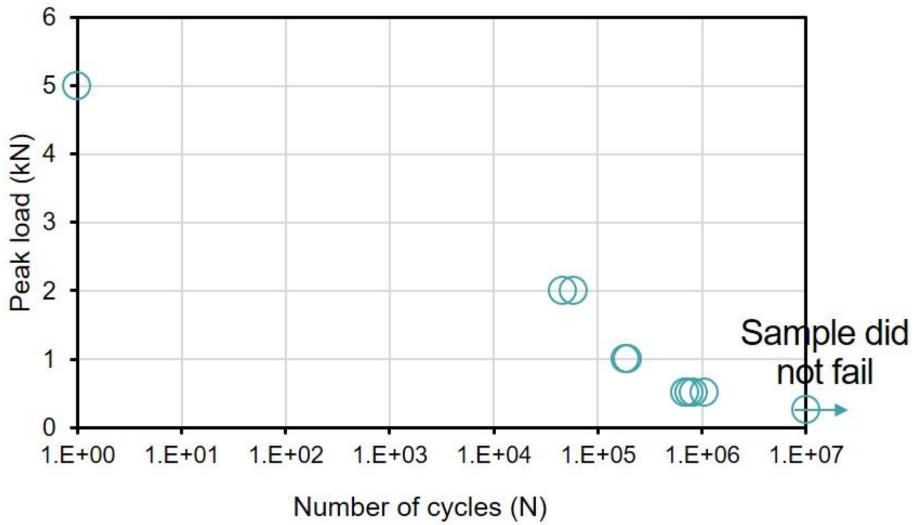

Fig. 13.2. Fatigue performance of F-SPR Mg/CFRP joints as a function of number of fatigue cycles.

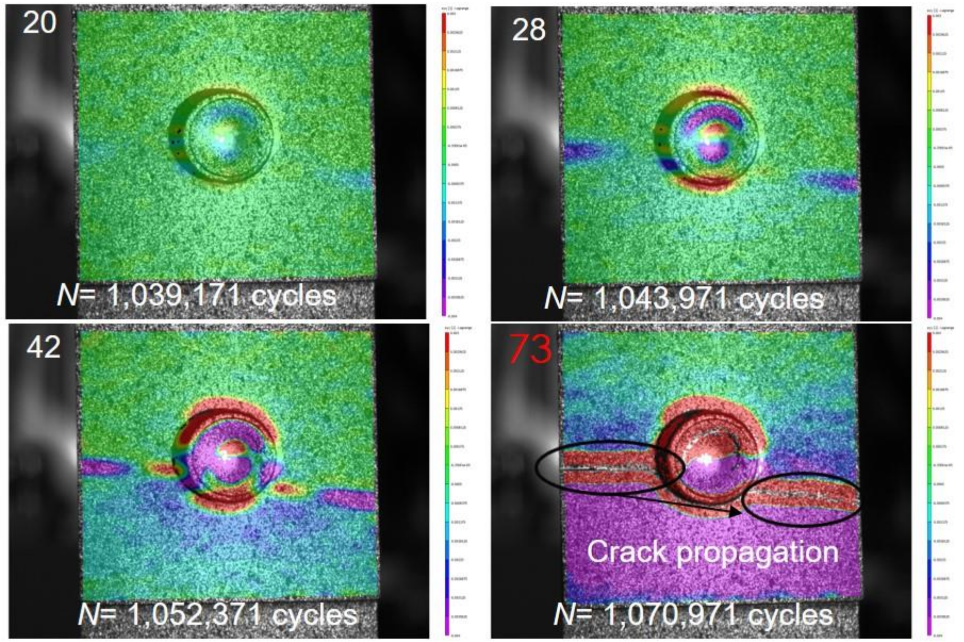

Fig. 13.3. DIC of F-SPR Mg/CFRP samples undergoing fatigue testing.

- Fatigue life of F-SPR joint is higher than the fatigue life of resistance spot welding of AZ31-AZ31 from open literature.

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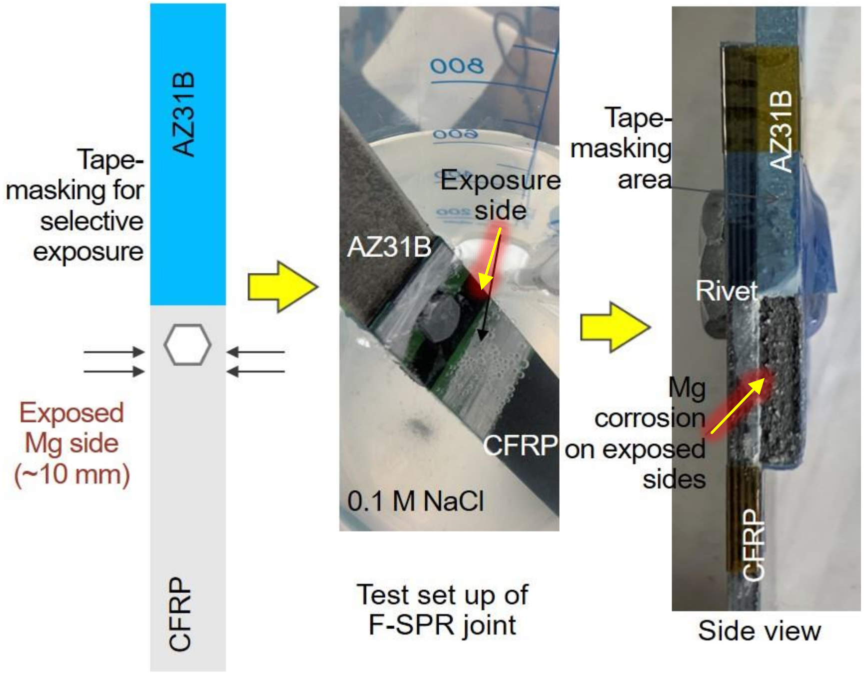
ACCOMPLISHMENT: TASK 2B. F-SPR

NOVEL APPROACH TO QUANTIFY GALVANIC ATTACK ON MG



Selective corrosion exposure

Resulted in measurable (quantifiable) Mg alloy corrosion to assess galvanic effect in the joints.

Fig. 14.1. Images showing the procedure for isolating Mg plates during corrosion testing.

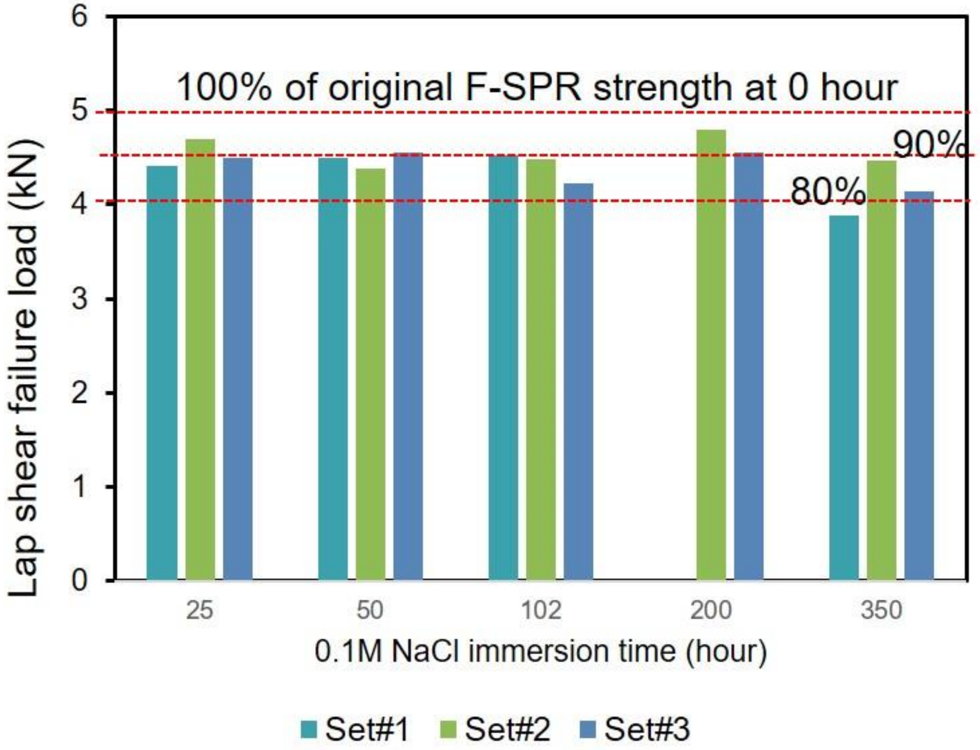


Fig. 14.2. Lap shear failure load of F-SPR Mg/CFRP after immersion in salt solution.

Material	TS CFRP	Steel rivet	AZ31B
E_{cor}	$0.23V_{SCE}$	$-0.6V_{SCE}$	$-1.55V_{SCE}$

Most noble (cathodic) Least noble (anodic)

Corrosion potential of individual materials which drives galvanic polarization of Mg when joined

ACCOMPLISHMENT: TASK 2B. F-SPR

NOVEL APPROACH TO QUANTIFY GALVANIC ATTACK ON MG

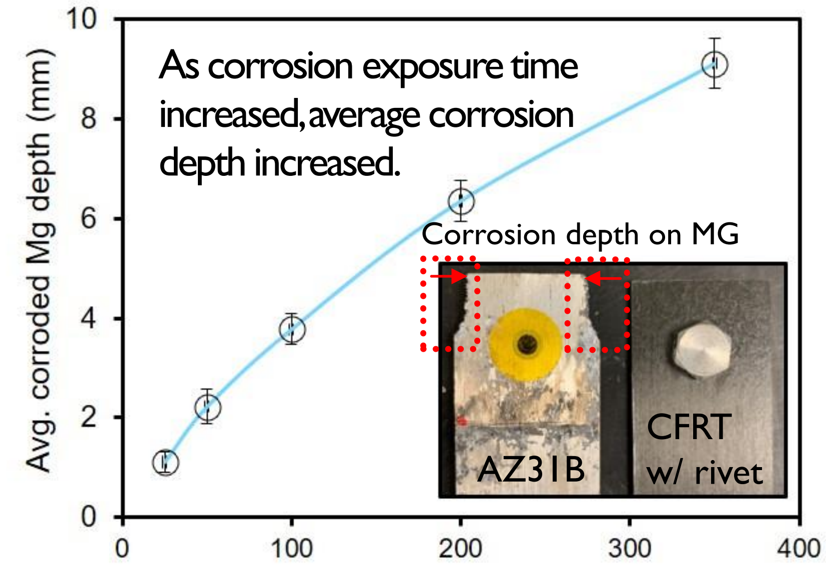


Fig. 15.1. Estimated average Mg corrosion depth as a function of immersion time in salt solution.

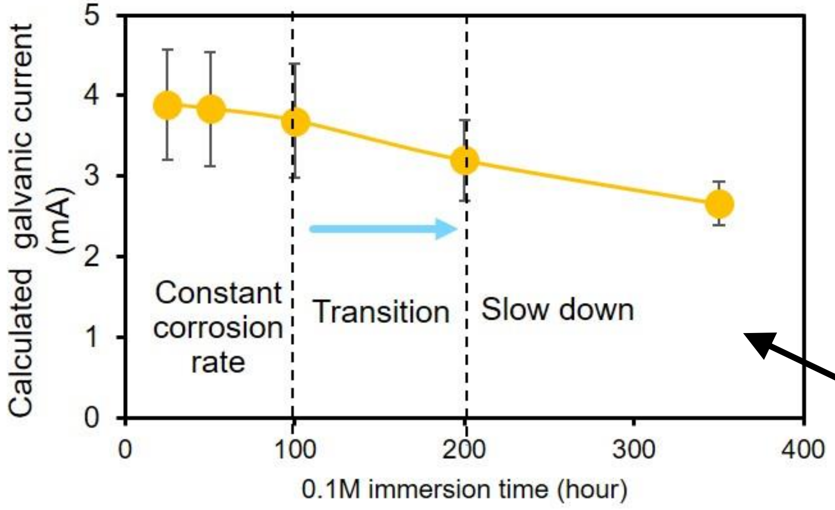
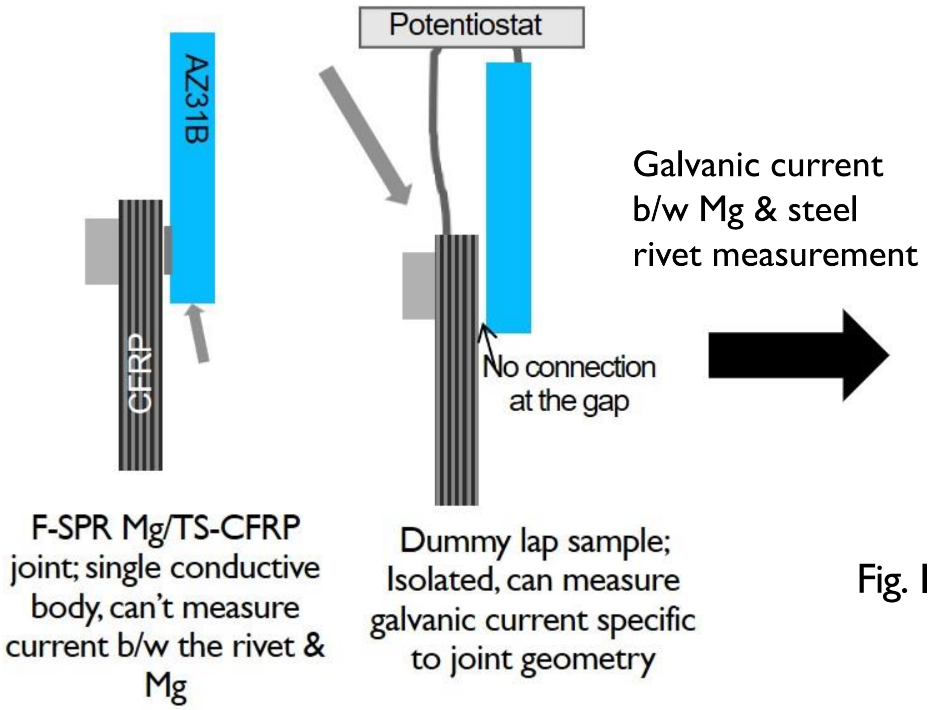


Fig. 15.2. Average galvanic current as a function of salt solution immersion time.



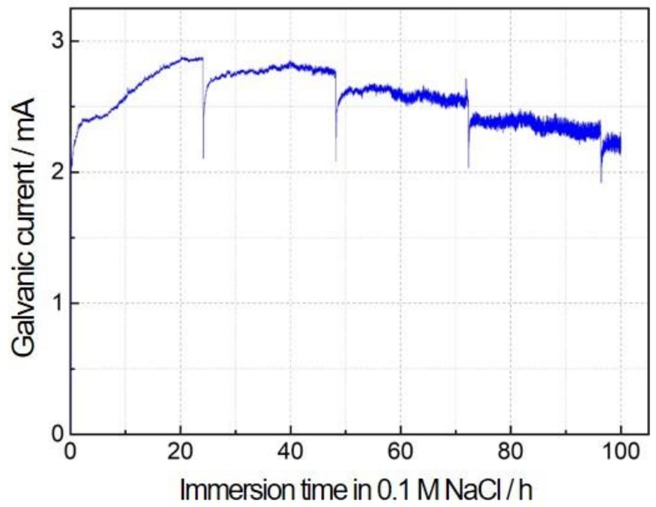


Fig. 15.3. Galvanic current measurement between Mg and CFRP plates.

Average mass loss rate and predicted galvanic current decreased as corrosion exposure time increased

– Transition between 100 and 200 hours

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RESPONSES TO PREVIOUS YEAR'S REVIEWERS' COMMENTS

Comment	Response
1a. The corrosion testing should perhaps focus on coated Mg or in some way isolate the behavior of the joint. 1b. Fundamental measurements of corrosion potential between couples, and not just apply a coating and look at the ASTM B117 test results	Accomplished in Task 2A and 2B in FY'19 to FY' 20.
2. Not clear how each of the teams are learning from one another and how those learnings are being applied.	Monthly meetings; biannual review meetings; informal discussions. Data provided to the Corrosion and IbD Tasks for inclusion in their current or planned future scope.
3. Fundamental measurements of corrosion potential between couples, and not just apply a coating and look at the ASTM B117 test results	ORNL performed corrosion potential measurements in addition to ASTM B117.
4. Better coordination with and aggressively marketing to industrial collaborators.	End of year 3 goals are developing collaborations with industry partners.

COLLABORATION AND COORDINATION

- Pacific Northwest National Laboratory
  - Keerti Kappagantula (Task 1 Lead), Piyush Upadhyay, Scott Whalen, Tianhao Wang, Hrishikesh Das, Madhu Pallaka
- Oak Ridge National Laboratory
  - Yong Chae Lim (Task 2 Lead), Jian Chen, Jiheon Jun, John Wade, Michael Brady, Leonard Donovan, Dave Warren (retired in Feb, 2020), Zhili Feng
- BASF – Thermoplastic plaques provided

REMAINING CHALLENGES AND BARRIERS

- Task 1: Friction Stir Interlocking
  - Quantifying corrosion between Mg/CF and Mg/CFRP pairs.

- Task 2a: Bolting
  - Mitigating general corrosion of bolt, nut, washer and Mg alloy.

- Task 2b: Friction Self-Piercing Rivet
  - Residual stress effect on the joint
  - Reducing galvanic corrosion of Mg by more noble rivet materials and/or coating

PROPOSED FUTURE WORK

- Task 1: Friction Stir Interlocking
  - Origins of damage in CFRP
  - Corrosion between AZ31B plate and CFRP at the joint interface
  - Peel testing for FSI – Linear joints

- Task 2a and 2b: Bolting and Friction Self-Piercing Rivet
  - Explore different coating and alternative materials for rivet to prevent galvanic and general corrosion: collaboration with coating companies
  - Complete characterization of corroded F-SPR joint
  - Optimize process and evaluation of mechanical joint performance F-SPR joint
  - Study of residual stress of F-SPR joint

Future work is subject to change based on funding levels

SUMMARY

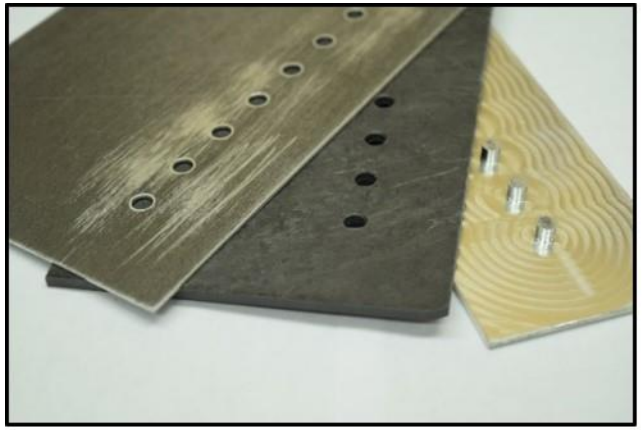
- Task 1: Friction Stir Interlocking
  - FSI – Linear joining process parameters optimized to minimize microstructural defects in ~ configurations.
  - Determined the effects of friction processing on the microstructure of Mg alloys and CFRP.
  - New method of riveting Mg and TP-CFRP: FSI – Spot joining was demonstrated as proof-of-concept.

- Task 2a: Bolting
  - Results from ASTM B117 438 hours exposure
    - Un-isolated joints showed significant galvanic corrosion on AZ31B with only 21.7% of original joint strength.
    - 3-step isolation showed 77.9% of original joint strength, confirming the isolation method effectively slowed down joint degradation.

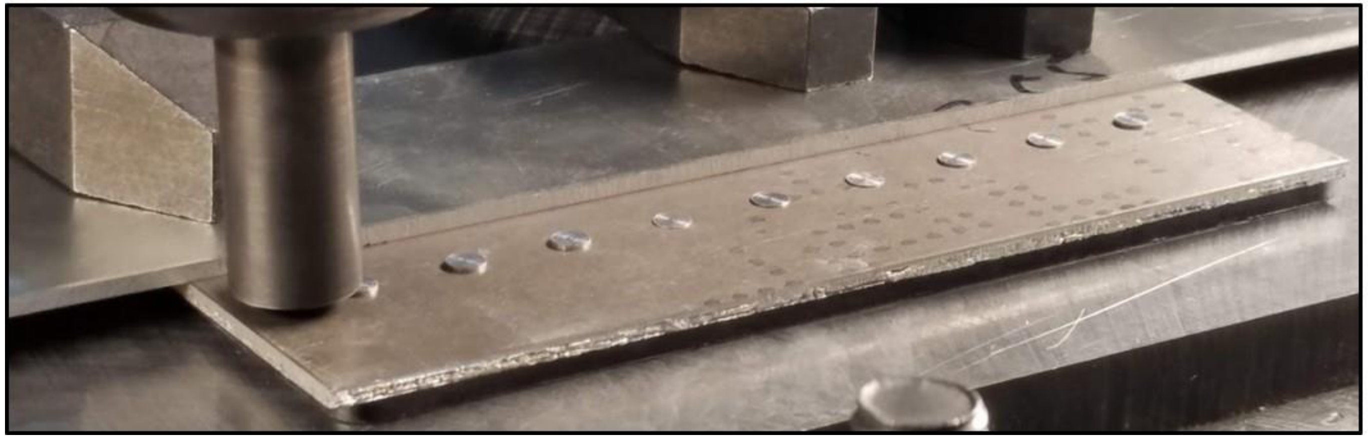
- Task 2b: Friction Self-Piercing Rivet
  - Fatigue life of F-SPR joint with steel rivet is longer than the fatigue life of resistance spot welding of AZ31-AZ31.
  - Quantification of galvanic corrosion of Mg alloy was achieved by selective exposure approach on Mg alloy.
  - Joint retained up to 80~90% of original strength after exposure to 0.1M NaCl for 350 hours.

TECHNICAL BACK-UP SLIDES

FSI – LINEAR JOINING PROCESS DEVELOPMENT



Mg backing plate with machined pins assembled with CFRP plate (left); Mg plate placed on top to complete the joint assembly (bottom left); FSI joint (bottom right)

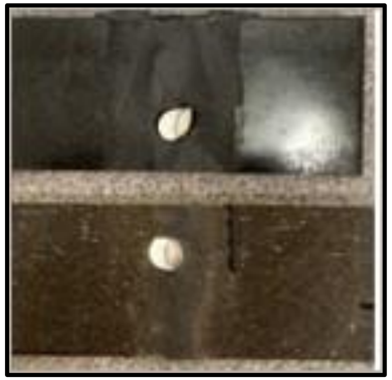


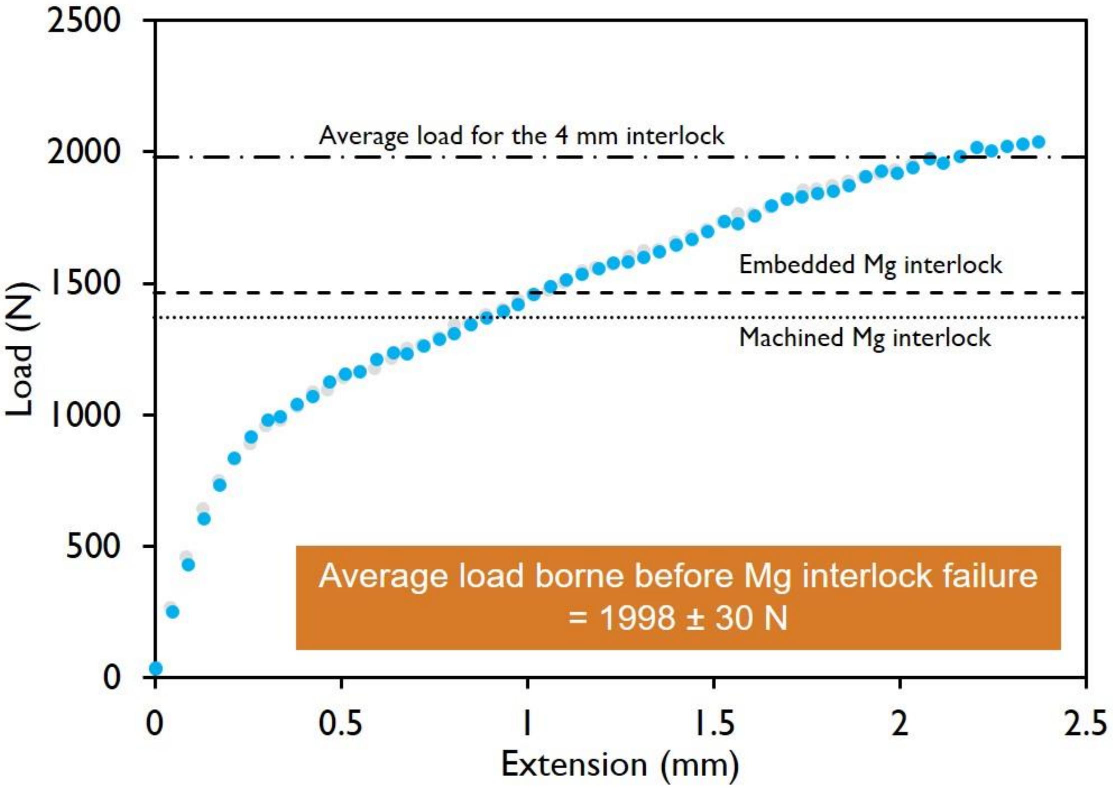
FSI processing

Controlling weld speed, rotation rate, plunge depth and tilt angle

BASE STRENGTH OF MG INTERLOCKS

- FSI – Linear joints fabricated using 4 mm diameter interlocks
- Process parameters modified from joints with 5 mm interlocks





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CORROSION MASS LOSS MEASUREMENT AND CALCULATION OF GALVANIC CURRENT OF F-SPR JOINT

From Faraday's law

$$m = \frac{QM}{Fz}$$

m (from experiment): mass loss (g)

Q (unknown): total charge transfer required to dissolve mass m, (unit C=A·s)

z: charge of ion, for Mg, z=+2

M: molecular mass, Pure Mg= 24.3 g/mole

F: Faraday's constant, F=96500 C/mole

$$\frac{m}{t} = \frac{QM}{Fzt} = \frac{IM}{Fz}$$

$\frac{m}{t} =$ mass loss rate (g/s),

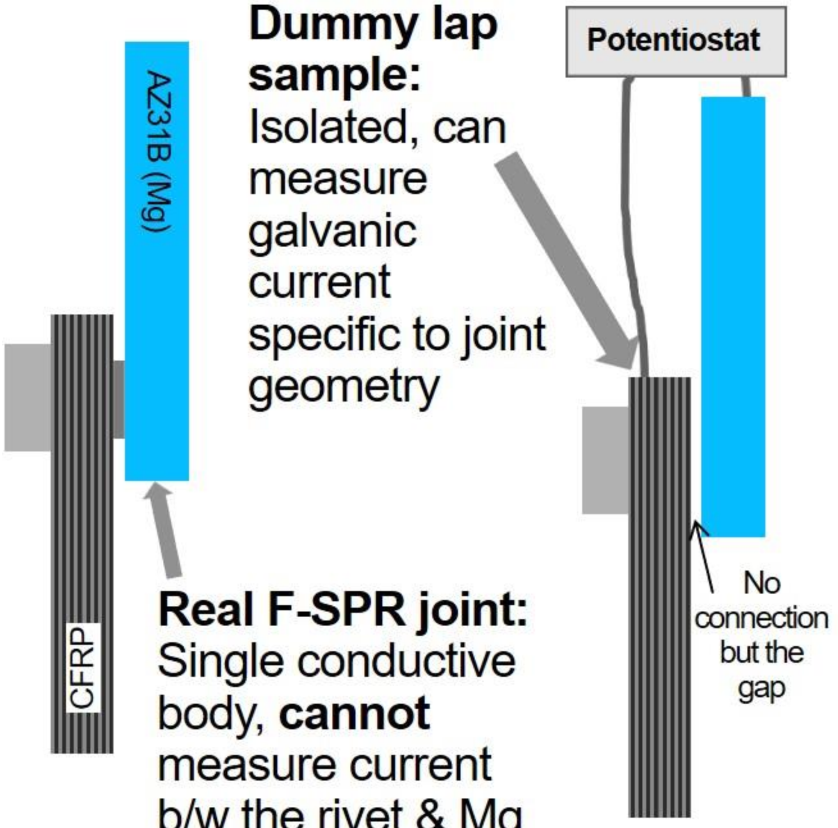
I (unknown): galvanic corrosion current, Ampere

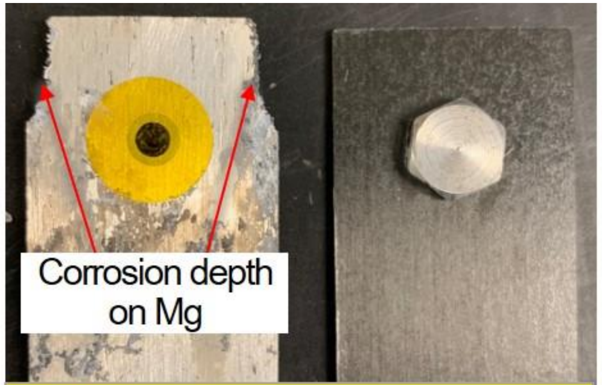
z: charge of ion, for Mg, z=+2

M: molecular mass, Pure Mg= 24.3 g/mole

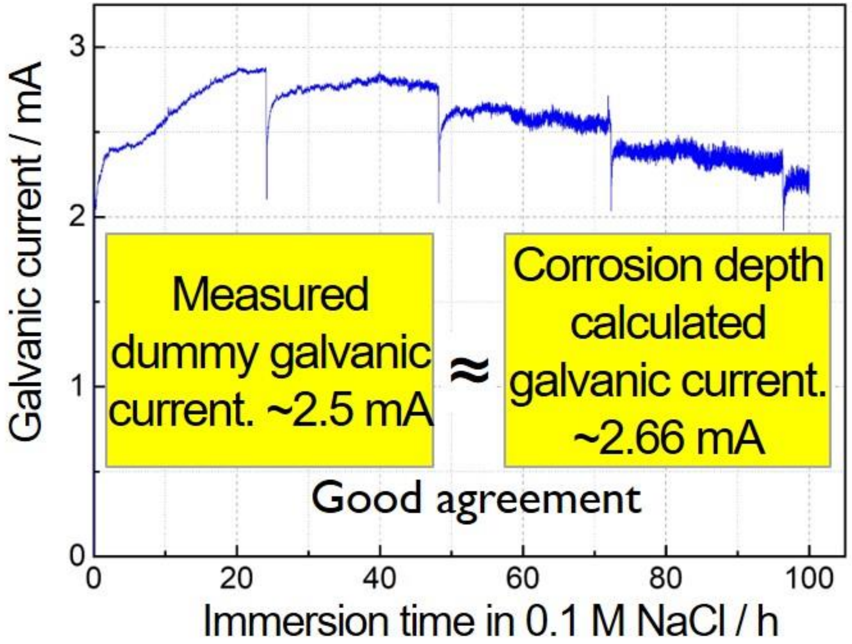
F: Faraday's constant, F=96500 C/mole

GALVANIC CURRENT MEASUREMENT USING “DUMMY” F-SPR SAMPLE





Disassembled dummy lap sample after 100 h immersion



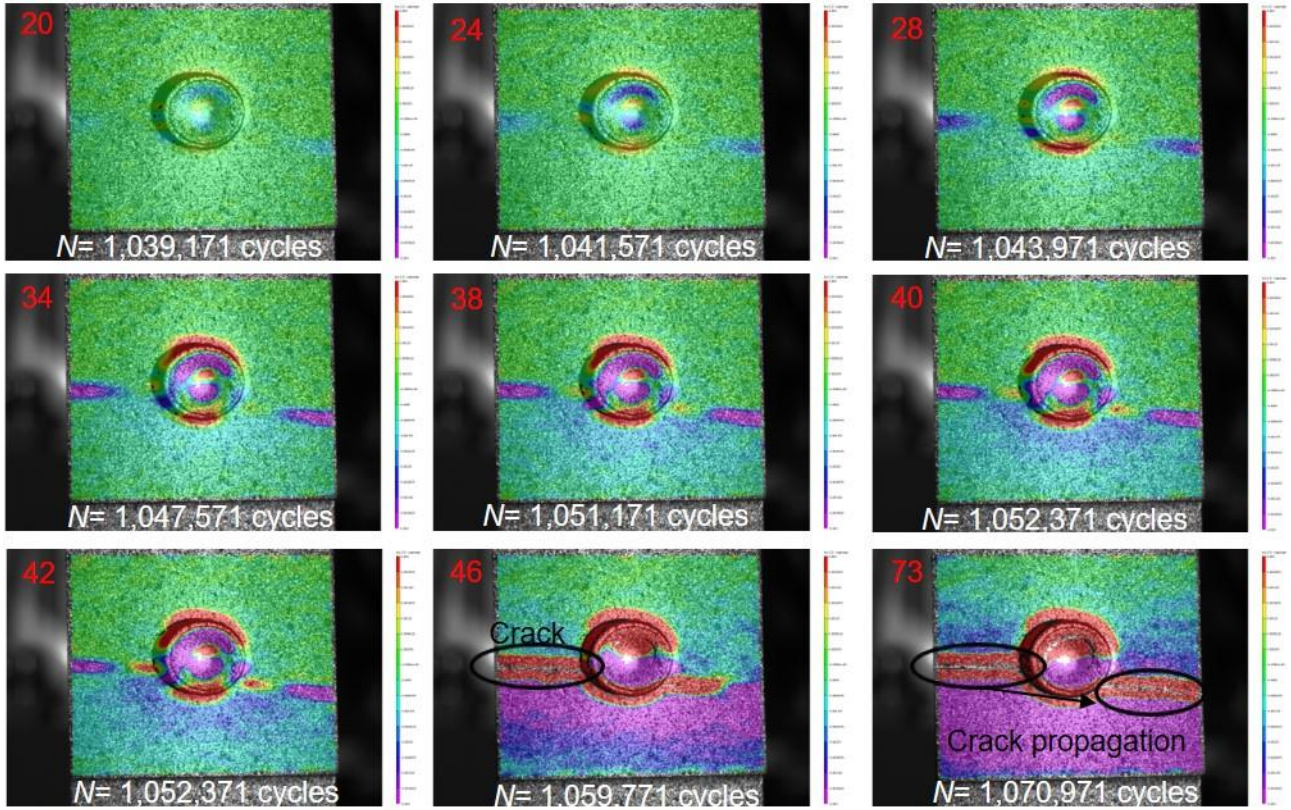
From Faraday’s law

$$\frac{m}{t} = \frac{QM}{Fzt} = \frac{IM}{Fz}$$

$\frac{m}{t}$ = mass loss rate (g/s) (measured from experiment)
I(unknown): galvanic corrosion current, Ampere
z: charge of ion, for Mg, z=+2
M: molecular mass, Pure Mg= 24.3 g/mole
F: Faraday’s constant, F=96500 C/mole

I(unknow) for F-SPR joint can be reversely calculated

DIC SNAP SHOP IMAGES DURING FATIGUE TESTING OF F-SPR (AFTER 1M CYCLES)



- *Peak load* = 2.0 kN
- N= 57,963 cycles

- *Peak load*= 1.0 kN
- N= 196,512 cycles

- *Peak load*= 0.5 kN
- N= 1,070,971 cycles

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